Title	An Aerodynamic Study of the Articulatory Mechanism in the Production of Bilabial Stop Consonants
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Citation	音声科学研究 = Studia phonologica (1966), 4: 70-80
Issue Date	1966
URL	http://hdl.handle.net/2433/52614
Right	
Type	Departmental Bulletin Paper
Textversion	publisher

STUDIA PHONOLOGICA IV (1966)

An Aerodynamic Study of the Articulatory Mechanism in the Production of Bilabial Stop Consonants

by

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The fact has been generally accepted that the production of the voiceless bilabial stop consonant /p/ passes through three phases; sometimes termed implosion, hold and explosion. The initial phase is described as consisting of firm velopharyngeal closure, closing of the lips and supply of air from the lungs. Building up the intraoral pressure with the tensed lips and cheeks characterize the second phase. The third phase consists of the quick release of the dammed up pressure by sudden opening of the lips resulting in a /p/ sound. The voiced bilabial plosive /b/ is formed in the same manner as /p/ except that the voiced /b/ is accompanied by a vibrating air column due to the vibration of the vocal folds.

Many details have been added to these basic views by a number of recent studies. The investigations on the articulatory actions, physiologic and physical processes and acoustic events during the production of the consonants have provided information valuable for: (1) understanding of the mechanism of speech perception and recognition, (2) the creation of the speech synthesizer, (3) understanding of the physiological mechanism involved in speech production, (4) the diagnosis and treatment of the specific speech defects. From the acoustic studies, (3) (5) (7) (8) (11) (17) (18), data has been gathered concerning the time duration, frequency spectrum, intensity of consonants and the formant transition under various phonetic environments. In addition, cinematographic, (6) (22), cineradiographic, (1) (16) (18) (19), and electrophysiologic investigations have clarified specific physiological processes during consonant production.

Since the acoustic properties of the consonant are structured by the interaction between rapid articulatory movements and transitory aerodynamic changes in the vocal tract, aerodynamic studies will contribute greatly to the better understanding of the relationship between the acoutsic and physiological aspects of consonant production.

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This work is supported by U.S.P.H.S. grant NB 06670-01 CMS.

Regarding the aerodynamic phenomena during the production of consonants, the analyses of the intravocal tract pressure and oronasal flow rate have been made by Black (2), Fischer-Jorgensen (4), Issiki (9), Kaneko (11), and Malecot (15). On the basis of the simultaneous records of the esophageal pressure, the intraoral pressure, and the flow rate variation during speech, Ladefoged (14) studied the effect of the articulation on the subglottic pressure. The results have provided information on the relationship between articulatory movements and laryngeal manifestations during speech. Warren (20) (21) has developed a method for the assessment of the size of the velopharyngeal opening during connected speech on the basis of the nasal air flow and oropharyngeal pressure measurements.

The measures of the nasal air flaw rate, oropharyngeal pressure, and intranasal pressure supply information on the impedance at the velopharygeal space. The simultaneous registration of these three factors will be essential for the accurate assessment of the velopharyngeal sphincter function during speech. In order to supplement the knowledge on the velopharyngeal sphincter function, we have attempted to measure the intraoral pressure, nasal pressure, and the nasal air flow rate durihg stop consonant production in normal and pathologic cases. In this report, the data on the bilabial stop plosives obtained from normal subjects will be discussed.

METHODS

Nasal air flow rate, volume of air emitted through the nose, nasal air pressure, and intraoral pressure were recorded simultaneously during the production of bilabial stop consonants. Two normal adults, male and female, served as subjects. The voiceless CV syllables /pa/, /pi/, and /pu/, and the voiced CV syllables /ba/, /bi/, and /bu/ were subjected to analysis. Each syllable was produced fifteen times in a constant normal manner with an approximate 1 sec time interval between each utterance.

Fig. 1 shows the experimental arrangement diagrammatically. Nasal air flow

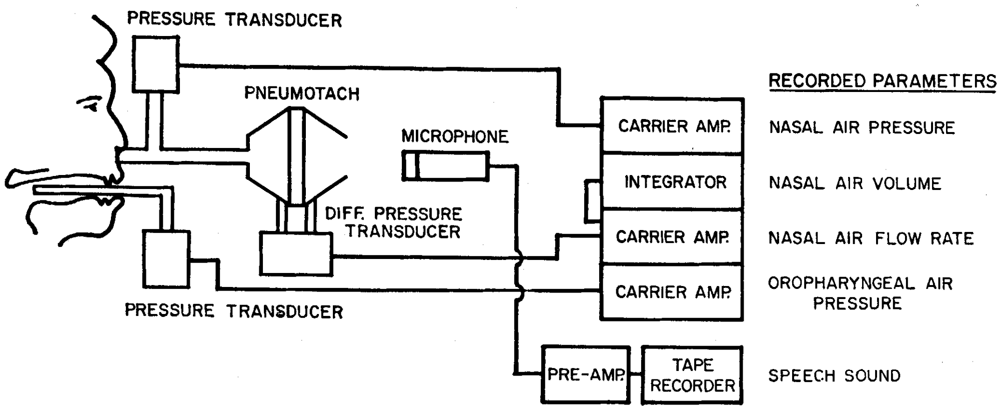

Fig. 1. Diagram of experimental arrangement.

rate was recorded by means of a pneumotachograph. One end of a specially designed T tube was applied to one nostril air tightly, while the other nostril was plugged with a small cotton ball soaked with physiologic saline solution. The opposite end of the T tube was connected with the pneumotachograph. The third end of the T tube was hooked up to a pressure transducer by a vinyl tube of 30 cm in length. Thus, the nasal air flow rate and the nasal pressure were transmitted to the transducers which converted air flow rate and pressure into electrical signals. The oral pressure was picked up by a vinyl tube whose distal end was placed on the anterior portion of the root of the tongue. The vinyl tube of 30 cm length conducted the intraoral pressure to the second transducer. The electrical signals from each transducer were amplified by the corresponding carrier amplifier and were registered with a polybeam recorder. The volume of air emitted from the nose was obtained by integrating the flow rate. The conversion from air flow rate to air volume was performed through an integrating amplifier.*

The calibration of the pneumotachograph system was made by a rotameter of less than one percent error at the maximum flow rate, and adjusted to allow 1 cm beam deflection at 100 cc/sec flow rate. The pressure measuring system was set to give 4 cm beam deflection at the pressure of 10 cm H_2O by the aid of a water manometer. The response time of each system was confirmed to be short enough to permit the mean flow rate and pressure during speech. The polybeam recorder was set at 5 cm/sec of paper speed.

The speech sounds were picked up by a condenser microphone (B & K ♯4134) placed 20 cm from the mouth, and recorded on one of the channels of a dual track tape recorder (Sony 777). The amplified and recorded speech sound waves were fed into one of the channels of the polybeam recorder.

Normal articulartory movements were not affected by the insertion of the tubes into the nostrils and mouth. Thus, we could register five parameters simultaneously: the nasal air flow rate, the nasal air pressure, the volume of air emitted through the nose, the intraoral pressure, and speech sound. The detailed observations and analyses were accomplished on the records obtained from 180 utterances of bilabial stop plosives.

RESULTS

Upon reviewing our total data, we found there are standard patterns in the nasal air flow, the nasal air pressure, and the oral pressure during the production of voiceless and voiced bilabial stop consonants. The typical relations between these three factors are schematically demonstrated in Figs. 2 and 3. As shown by

* The transducers, carrier amplifiers, integrating amplifier, and polybeam recorder used in this experiment were: pressure transducer Sanborn ♯268B, and ♯267A, bidirectional differential gas pressure transducer Sanborn ♯270, carrier preamplifier Sanborn ♯350-1100B, integrating preamplificer Sanborn ♯350-3700, and polybeam recorder Sanborn ♯586-100.

these figures, a small amount of air emission through the nose starts simultaneously with the rise in the oral pressure. Corresponding to this air emission through the nose, a slight increase in the nasal air pressure is recorded. When the oral pressure reaches a certain level, both the nasal air flow rate and the nasal air pressure decrease gradually to zero. After completion of this stage, a very

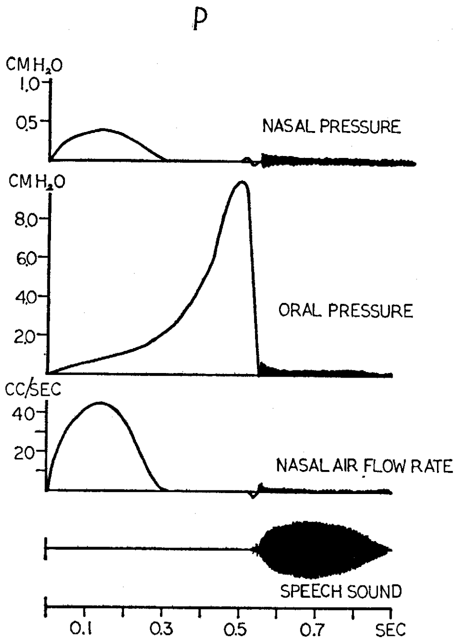

Fig. 2. Schematic drawing of typical nasal air flow rate, nasal pressure, and oral pressure pattern during the production of the Voiceless Bilabial Stop P+Vowel syllable.

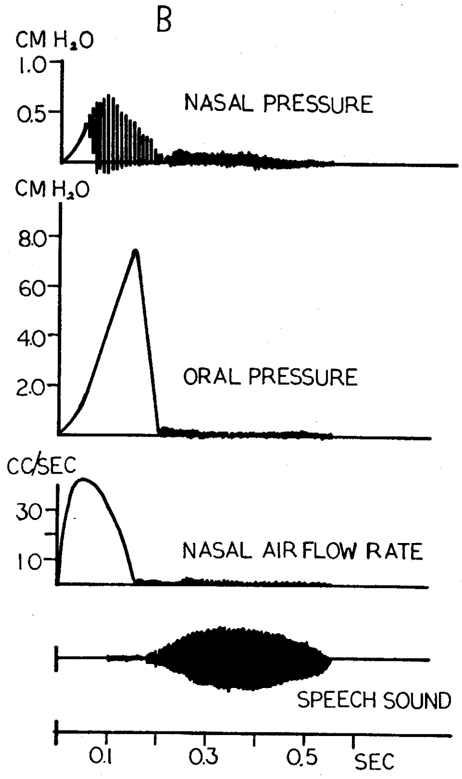

Fig. 3. Schematic drawing of typical nasal air flow rate, nasal pressure, and oral pressure pattern during the production of the Voiced Bilabial Stop B+Vowel syllable.

sharp elevation of the oral pressure continues and it reaches a maximum level. The oral pressure then suddenly changes decreasing to the minimum level which corresponds to the sound pressure of the subsequent vowel. The oscillations of the vowel sound waves starts when the oral pressure reaches this minimum pressure.

On the basis of these characteristic findings, measurements were made with regard to time duration, pressure, flow rate and volume of air as follows: 1) Duration of oral pressure rise, oral pressure drop, nasal air emission, nasal air increase, and vowel sound, 2) maximum oral pressure, oral pressure corresponding with the highest nasal air flow rate, oral pressure corresponding with the termination of nasal air emission, and the nasal air pressure peak, 3) maximum nasal air flow rate and 4) air volume emitted through the nose.

Figs. 4, 5, and 6 summarize the data concerning the oral pressure during the

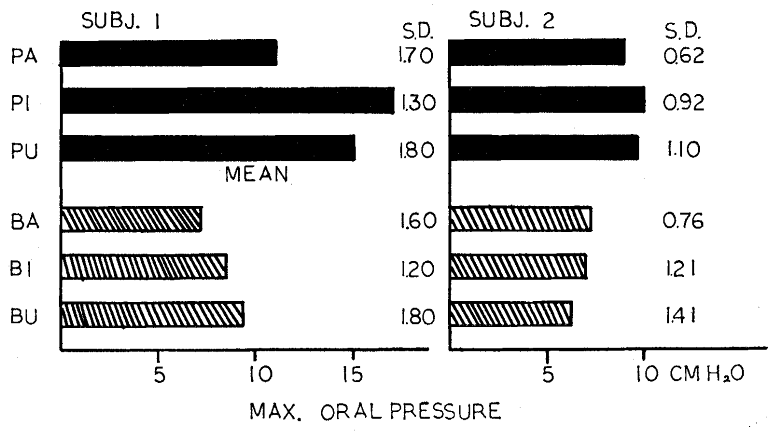

Fig. 4. Columns show mean time duration of oral pressure rise. S.D. indicates the standard deviation of the mean value. Note significant difference in time duration between the voiceless and the voiced stop.

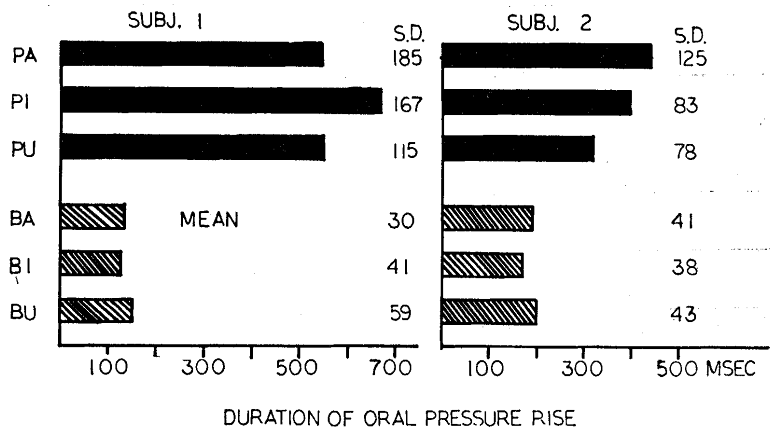

Fig. 5. Columns show mean of the maximum oral pressure. S.D. indicates the standard deviation of the mean value. The voiceless stop is associated with higher oral pressure. /Pi/ and /pu/ show higher oral pressure than /pa/.

production of the bilabial stops. Figs. 4 and 5 indicate that there are significant differences in the duration of oral pressure rise and the maximum oral pressure between the voiceless and the voiced stops. The production of voiceless bilabial stops showed longer duration of the oral pressure rise and higher oral pressure than that of the voiced stops. In order to dam up the oral pressure, the periods ranging from 300 to 800 miliseconds were necessary for the voiceless stops, whereas for the voiced stops, the periods ranged only from 100 to 200 miliseconds. These time and oral pressure relationships reveal that there are also differences in the velocity of oral pressure rise between the production of voiceless and voiced stops. Table I gives the mean velocity of the oral pressure rise. It is clearly indicated

Table 1. Mean velocity of oral pressure rise in cm H_2O/sec. More rapid velocity is notable in the voiced bilabial stops.

	Subj. 1	Subj. 2
PA	20.2	20.2
PI	23.2	25.0
PU	27.2	29.0
BA	56.5	37.4
BI	67.0	41.0
BU	62.0	32.0

that the production of the voiced bilabial stops undergoes a more rapid rise of the oral pressure even if the absolute maximum oral pressure is lower than that of the voiceless stops.

As shown by Fig. 6, there was no consistent difference between the production of voiceless and voiced stops in regard to the duration of the oral pressure drop. However, it is notable that /pi/ and /pu/ show higher oral pressure and a longer oral pressure drop time than /pa/. As a result, /pa/ shows a faster pressure drop than

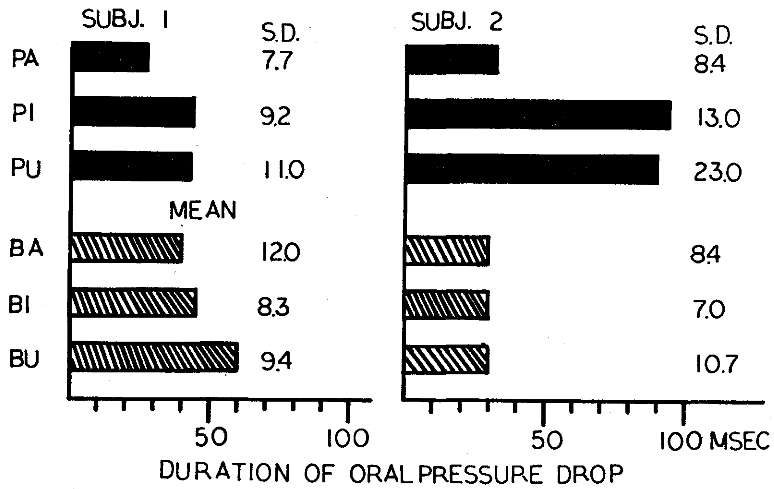

Fig. 6. Columns show mean duration of oral pressure drop. S.D. denotes standard deviation. Note shorter duration in /pa/ compared with /pi/ and /pu/.

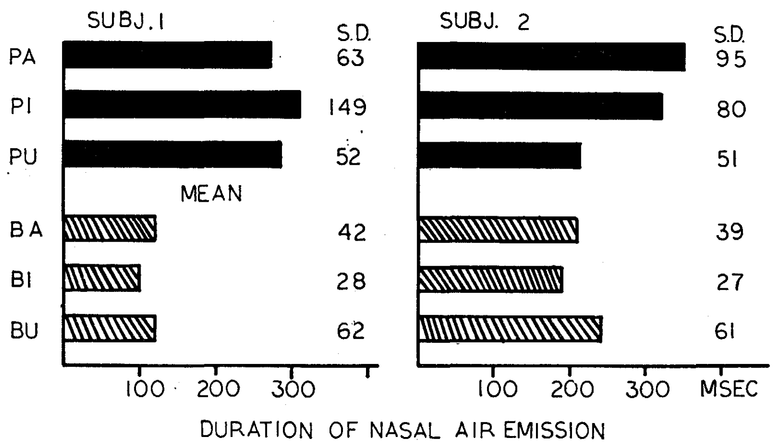

Fig. 7. Mean time duration of nasal air emission and its standard deviation. Notable difference between the voiceless stop and the voiced stop is shown.

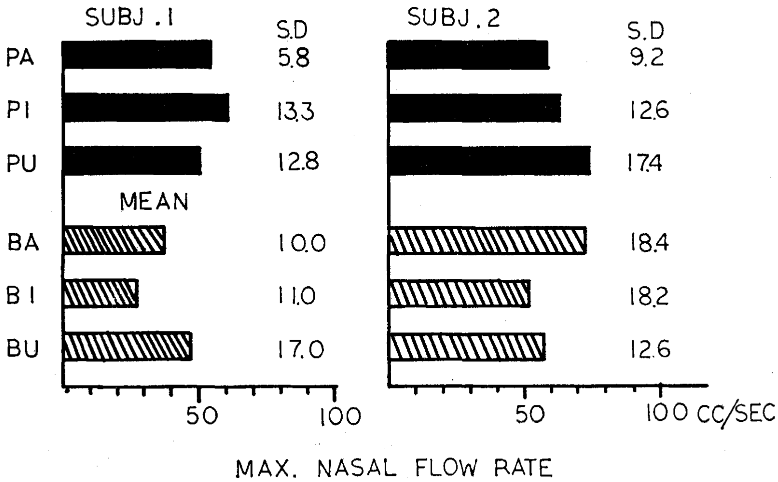

Fig. 8. Mean of maxsmum nasal air flow rate and its standard deviation. No significant difference between the voiced stop and voiceless stop is observed.

Table 2. Time duration ratio of the oral pressure rise to nasal air emission in percent. Greater values noted in the voiced bilabial stops indicate air escape continues almost throughout or at times beyond the phase of the oral pressure rise.

	Subj. 1	Subj. 2
PA	50	80
PI	47	80
PU	56	66
BA	92	110
BI	78	112
BU	80	120

/pi/ and /pu/.

Figs. 7 and 8 summarize the data regarding the air emission through the nose. As is shown by Fig. 7, the duration of the nasal air emission is shorter in the voiced stops compared with the voiceless stops. In the voiceless stops, the duration fluctuates between 200 and 350 miliseconds, whereas in the voiced stops, the duration varied from 100 to 250 miliseconds. Table 2 shows the time ratio of the oral pressure rise to the nasal air emission. It is indicated by this table that the air emission through the nose continues almost for the whole period of the oral pressure rise or even beyond the peak of the oral pressure in the case of voiced stops. By contrast, in the production of the voiceless stops, the nasal air leakage is usually blocked before the attainment of the maximum oral pressure. When the oral pressure reached about 2.5 cm H_2O in subject 1 and 5.5 cm H_2O in subject 2, the nasal air flow rate decreased to zero during the voiceless stop production.

Fig. 8 demonstrates that there is no remarkable difference in the maximum nasal air flow rate between the voiceless and voiced stops. It fluctuates between 20 cc/sec. and 100 cc/sec. regardless of voicing or the succeeding vowel environment. Corresponding to the maximum nasal flow rate, approximately 1 cm H_2O of oral pressure rise was noted.

Associated with the nasal air emission, a slight elevation of the nasal pressure was observed. The accurate measurement was limited by the sensitivity of the present instrumental set up. However, in the selected materials, we found the nasal pressure reaches about 0.3 cm H_2O.

The volume of air emitted through the nose was often too small to permit exact measurement. An estimation of less than 20 cc of air escapes through the nose during the production of bilabial stop consonants.

A typical record showing these findings are presented in Fig. 9.

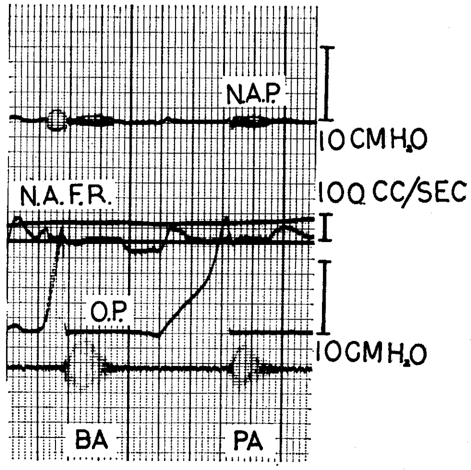

Fig. 9. Simultaneous registration of the nasal air flow rate (N.A.F.R.), nasal air pressure (N.A.P.), oral pressure (O.P.) during the productions of /ba/ and /pa/.

Discussion

The present study reveals that a *complete velopharyngeal* closure is not an absolutely essential factor for building up the oral pressure during the production of the bilabial stop plosives. It is commonly noted that the nasal air emission starts simultaneously with the initiation of the oral pressure rise. In the case of the /p/ sound, the nasal air emission terminates before the oral pressure reaches its peak. During the production of the /b/ sound, the nasal air emission often continues even beyond the attainment of the maximum oral pressure. These findings indicate that the velopharyngeal space still remains open until the oral pressure rises to a certain extent. The maximum velopharyngeal sphincter action is achieved when the oral pressure is elevated above a certain level.

Björk (1) in his cineradiographic analysis synchronized with the sound spectrographic record, observed that there was incomplete velopharygeal closure during the /p/ and /b/ sound in about 10% of his fifty total cases. He stated further that there was also the possibility of error in his method of assessing the frame on which velopharyngeal closure was complete, because of the short duration of the sound.

Observations of data from the present study on the interrelationships between nasal air flow and oral pressure rise suggest the voiceless bilabial stop /p/ can be produced through the following stages: (1) lip closing, (2) narrowing of the velopharynx synchronous with the air supply from the lungs, (3) completion of the naso-oral air block, (4) sharp elevation of intraoral pressure, and (5) sudden release of the air with quick opening of the lips. Anticipation of voicing during the oral pressure rise, and the less tight but rapid closure of the velopharynx may specify the articulatory process of the voiced bilabial plosive /b/.

Several preceding investigators have pointed out that there were differences in the aerodynamic patterns between the voiceless consonants and their voiced cognates. Isshiki and Ringel (9) reported that the absence of voicing for a given consonant was associated with a greater rate of air flow than during the production of its voiced cognate. Regarding the intravocal tract pressure, Malecot (15), Black (2), Kaneko (12), Fischer-Jorgensen (10) and Warren (20) have found that voiceless consonants are associated with the greater pressure than the voiced counterparts. The data obtained by the present investigation on the bilabial stop consonants support their conclusion.

In addition, our results reveal that there are notable differences in the time duration of the oral pressure rise; the voiceless stop /p/ shows a longer duration for building up higher oral pressure, and by contrast, the voiced stop is produced with a lower pressure rise of a shorter time duration. Further, the velocity of the pressure rise is found to be much faster in the voiced consonant /b/ production than the voiceless /p/ production. The identical findings were observed in the graphs of Isshiki and Ringel (9), and Ladefoged (14). In this respect, Ladefoged (16) mentioned that the relatively slow build up of the mouth pressure in the voiced stop /d/ and voiced fricative /v/ may be compared with the more rapid increase in /p/ and /f/. However, closer inspection of his graphs revealed the duration of oral pressure rise in /p/ was longer than in the other three consonants. These findings suggest the importance of the time factor for differentiation of the voiced from the voiceless articulatory process.

Fujimura (6) conducted the analysis of lip movements during bilabial stop consonants in one subject by the use of stroboscopic cinematography. He found the effects of phonetic environments on the lip opening process to be considerable. The movement is particularly rapid when a tense bilabial stop consonant is in the initial position of a word. Warren (20), on the basis of oropharyngeal pressure measurements, concluded that the pressure amplitude for the individual consonant is influenced by the phonetic content. In our CV syllable study, it is indicated that /pi/ and /pu/ showed higher pressure and longer oral pressure drop time than /pa/. Whereas no such difference can be noted in the voiced syllables.

The present study was confined to the bilabial stop consonants, and a limited scope of phonetic activities. Regardless of these restrictions, results obtained in this article clearly indicate that the technique reported is very promising for the accurate assessment of the velopharyngeal sphincter function during speech. Further extension of the present investigation currently in progress is essential to provide additional information on the articulatory process.

SUMMARY

In order to assess the velopharyngeal sphincter function during speech, the simultaneous registrations of the nasal air flow rate, the volume of the emitted

air through the nose, the nasal air pressure, the oral pressure and the speech sounds have been attempted. The results of the present study on the articulatory mechanism of the bilabial stop consonants indicate the technique is reliable and promising for the accurate assessment of the articulatory processes, especially velopharyngeal sphincter function during speech.

On the basis of detailed analyses of one hundred eighty utterances obtained from two normal subjects, the following conclusions are suggested:

1. During the production of bilabial stop consonants, the velopharyngeal space usually remains open until the oral pressure rises to a certain extent. The maximum velopharyngeal sphincter action is achieved when the oral pressure is elevated above a certain level.

2. Voiceless bilabial stop /p/ is produced with higher oral pressure rise of longer duration. The voiced bilabial stop /b/ undergoes a more rapid rise of the oral pressure of lower peak.

3. The production of the voiceless bilabial stop /p/ showed a tighter closure of the velopharynx than the voiced stop /b/.

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